Seismological Measurements for Site Effect Investigation in Nice, France

E. Bertrand, J. Régnier, F. Vinatier, Ph. Langlaude & M. Pernoud
CETE Méditerranée, Laboratoire de Nice, France

SUMMARY:
The quantitative assessment of site effects is a major topic in seismic hazard and engineering seismology studies. Frequency dependent site amplifications are known to be caused mainly by reverberations and the resonance effects of S-waves within either unconsolidated sediments overlaying stiffer formations or within topography. Both of these configurations can be found in the city of Nice, France. In 2008 we installed a temporary array throughout the city. Since then, the stations, composed of a Le3D velocimeter coupled with a Kephren digitizer, have been continuously recording the surface ground motion. Six stations are installed on rocky hills, while six others form a cross section in the Var valley. More than 40 regional earthquakes with an Mw of up to 4.9 have already been recorded. To analyze the site response at lower frequencies, we also studied several teleseismic recordings. The classical data processing, conducted to recover the seismic site response, show a particularly important ground motion de-amplification at the foot of the Mont Boron, a hill that shapes the eastern relief of the city. In the western part of the city, the temporary array helps us to depict the variability of the site responses across the Var valley.

Keywords: seismological experiment, site response, site effects, topographical effects

1. INTRODUCTION

September 19, 1985, the Michoacan earthquake generated severe damage in Mexico City, however located at more than 350km from the epicenter. An important seismic amplification is at the origin of the large damage observed in the city. The Provence earthquake of 1909 destroyed many villages located on the top of hills because of topographical site effects (Glinsky and Bertrand, 2011). These examples show that seismic movements can be strongly modified according to sub-surface geological conditions (presence of sedimentary or alluvial layers for example) or relief. Quantitative assessment of site effects is thus a major issue in seismic hazard and engineering seismology studies. The frequency dependent site amplifications are known to be mainly caused by resonance effects of S-waves within unconsolidated sediments overlaying stiffer formations or within topography.
The studied area is situated in the southeast of France at the junction between the Alps and the Ligurian basin. In this zone, a moderate but regular seismicity is recorded. Indeed, every 4 to 5 years, an earthquake with a magnitude larger than 4.5 occurs (Salichon et al. 2009). The most recent one struck the area the 7/7/2011 (Mw = 4.9; https://geoazur.oca.eu/spip.php?article1149). Its epicenter was located offshore Corsica Island, far enough not to produce any damage in Nice even if most of the local population felt it. Some destructive earthquakes have however hit the region already in the past. In 1564, an inland earthquake destroyed a village located 50 km north of Nice, causing several casualties (Lambert et al. 1994). In 1887, a major earthquake of intensity X (MSK) occurred offshore in the Ligurian sea, close to the Italian coast. This event caused the death of more than 600 people in Italy and a few casualties on the French Riviera between Menton and Nice. Its magnitude was estimated to be at least M=6.3 (e.g. Ferrari, 1991). Recent studies make the hypothesis that this kind of event could also occur closer to Nice (e.g. Salichon et al., 2009, Bour et al., 2003), increasing the seismic risk in the city. In order to better predict what would happen to the building in the city in such

scenario, as well as for preparedness concern, it is thus of importance to study the local hazard in the city.
Nice spreads over 72 km2 and roughly 20% of the city is built upon recent alluvium deposits. Other parts of the city are built upon Jurassic and Cretaceous rocky outcrops to the east and thick Pliocene conglomerates to the west (Fig. 1). Nearly 450 existing boreholes located mainly in the alluvial valleys were used to build a 3D geotechnical model of the area (Bertrand et al., 2007). This borehole database is often updated by the local authorities and contains data from the early fifties to nowadays. Because they are essentially linked to the development of the city, the boreholes are made at places where constructions are planned (such as network or important building). Thus their distribution is rather heterogeneous over Nice. In the valleys moreover, less than 40% of the boreholes are reaching the rocky basement. As an extended boring survey was not feasible because of its cost, the CETE Méditerranée seismic risk team carried out several seismological investigations for several years to complete this data set and to provide more constraints to the model. Traditional seismic profiling was also not intended, as it is not possible to use intensive explosive sources in town. Several passive experiments have thus been conducted throughout the city since the early nineties (Duval, 1996). We took advantage also from the French permanent accelerometric network, which has set up also 6 stations in Nice since 1995 (Fig. 1). The data recorded at this network have been already used to study the seismic local hazard (Douglas et al., 2008; Salichon et al., 2009; Drouet, 2006). They show large amplification at the stations located in the sedimentary basin but also a kind of deamplification at the station set up on the Jurassic hill (NBOR), which was considered as a reference station for Nice. The largest amplification has been observed at station NALS. Here the 1Hz seismic motion seems to be 20 times larger than the one recorded at station NBOR.
Because the very simple H/V technique on ambient vibration was proven to be suitable for microzoning studies although some limitation were pointed out when dealing with 2D or 3D structures, we measured ambient vibration at almost 500 points distributed in the city (Fig. 2). The recordings were processed according to the Nakamura technique (Nakamura, 1989) obtaining thus the fundamental resonance frequency of the sedimentary infill at each recording point. Considering the shear wave velocity in the sediment obtained from the analysis of the available borehole data, we were able to locally constrain the depth of the bedrock thanks to the well-known $f_o=V_s/4H$ equation. The amplification of the seismic motion occurs between 1 Hz and 2 Hz in the center of the alluvial filling. This frequency is increasing when approaching the edge of the basins. The resulting model (Fig. 2) shows a alluvium thickness maximum of 108 meters in the southwestern part of the city. In the other parts of the valleys, we observe bedrock depths reaching locally 80 meters.
In order to better constrain the seismic hazard in Nice, a temporary array composed of 12 seismological stations has been gradually set up throughout the city in different geological and topographical site conditions since late 2008 (Fig. 1).
Half of the stations have been installed in the Var Valley western of Nice (KARE, KCGA, KCAD, KSUB, KSLA and KMAU). This valley, is 1.2 km wide and is bordered by small hillside where Pliocene conglomerates outcrop on a height close to 200m. These conglomerates were deposit in a former delta of the river and overlay Pliocene marl. The area results from the plio-quaternary evolution of the alpine landscapes at the time of sea level variations and tectonic readjustments. Indeed, at the end of Miocene, a marine regression involves the digging of a deep canyon currently immersed off the airport of Nice. The plaisancian transgression that goes up to 20 kilometers inside the land produces the deposit of marl sediments that moves, in a final phase, into thick conglomerates of several hundreds of meters. Lastly, the quaternary alternation of regressions and transgressions, in particular the large wurmian regression, models the current plain and guides the installation of the alluvial terraces that borders it. The valley sediments are mainly composed of alluvial deposit with variable thickness alternating sands, clays, gravel and pebble. Previous geophysical and geotechnical studies show that in the studied area the bedrock could be reached at a maximum of about 200 m depth and that its geometry is rather complex.
The six remaining stations are used to investigate the seismic response of the eastern hills and the Pliocene conglomerates in order to better define a possible reference station for Nice (KVIC, KPOU, KACA, KOBS, KCER and KMAR). KVIC and KPOU are recording on the Pliocene conglomerates whereas the other have been used to investigate the response of the site on eastern Jurassic and cretaceous limestones forming the mount Boron and mount Gros. KACA and KOBS are installed

close to the top of the mount Gros (372 m altitude), KCER and KMAR are located down the mount Boron, at roughly 10 m and 50 m altitude respectively.

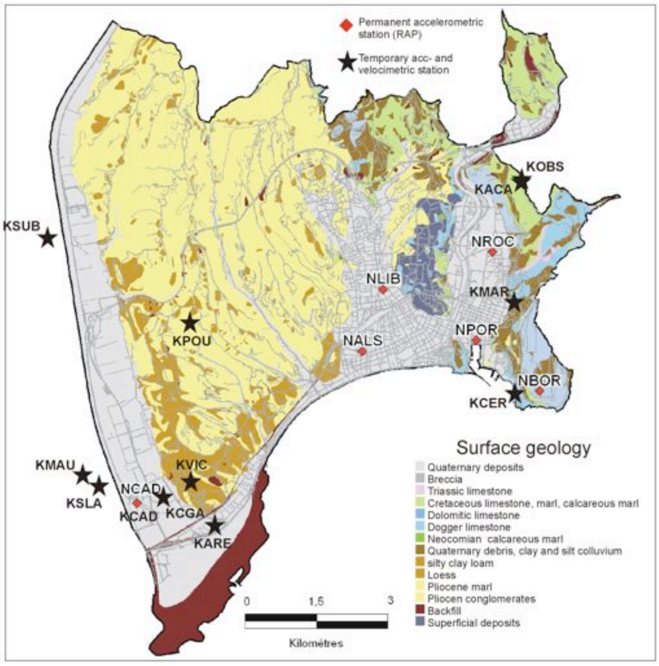

Figure 1. Geological settings and seismological arrays in Nice. The surface geology contour matches the city limits. KSUB, KMAU and KSLA are situated outside the city of Nice in the sedimentary basin of the Var valley.

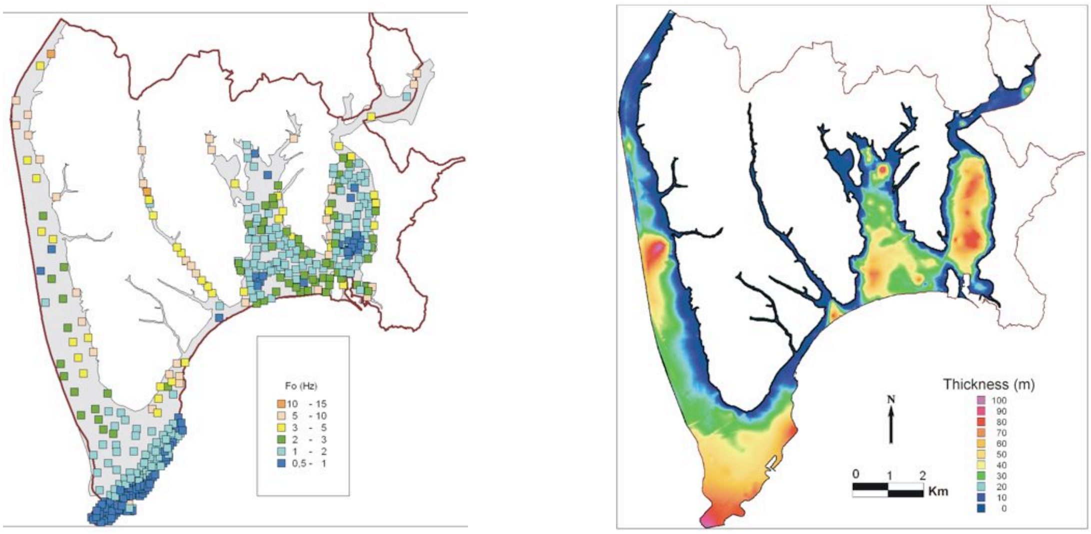

Figure 2. Results of the H/V on ambient vibration computation and geotechnical model of Nice sedimentary basins (Bertrand et al., 2007).

2. DATA

The seismic stations have been equipped with Lennartz Le3d-5s velocimeters and Geosig AC23 accelerometers coupled with 12-bits digitizers (Ageocodagis Kephren). For the purpose of this paper, the velocimetric recordings were the only one used. The transduction of these sensors is equal to 400 mV/mm/s and their natural frequency is close to 0.2 Hz. In most of the case, electricity has been supplied to the station and the time accuracy is guaranteed by GPS antenna connection. The accelerometric and velocimetric sensors have mostly been installed either inside or next to small

buildings. Except for KCER, recording the ground motion in a cave at the bottom of the Mount Boron and KOBS, set up in the basement of the astronomical observatory dome building. The stations are continuously recording the ground motion at a sample rate of 150 Hz. Between the beginning of its installation and the end of 2010, the temporary network recorded 110 workable earthquakes including 42 local events (epicentral distance smaller than 500 km) and 68 teleseismic earthquakes (Fig. 3). For the teleseismic events, the larger magnitude is equal to 9.0 (Great Tohoku earthquake), whereas for the local events the magnitude is ranging from 1.7 to 4.9 (Mw). During the experiment the people have felt a couple of local earthquake. The strongest shaking was due to the 7/7/2011 earthquake.
Fig. 4 gives an example of a typical set of recordings at the temporary array. The figure shows the East-West component of the ground shaking during the earthquake of the 4 July 2010. The epicenter was located 76 km eastern KCER station and its magnitude (Mw) has been evaluated by the ReNaSS (the French seismological survey) at 3.7. Among the rock sites, KCER shows the weakest motion and KOBS the strongest. The recording at KMAR, KPOU and KVIC seem to be almost equivalent even if KPOU and KVIC are about 7 km further away from the epicenter than KMAR. In the Var valley, the ground motion seems to be the smallest at KSLA station and the largest at KCGA. The motion at this latter station appears to be of the order of the one recorded at KOBS station even if the soil condition is singularly different. KOBS may thus not be considered as a good reference station. The differences observed between the time histories recorded at the stations in the Var valley point out the variation of the seismic soil response throughout the basin.

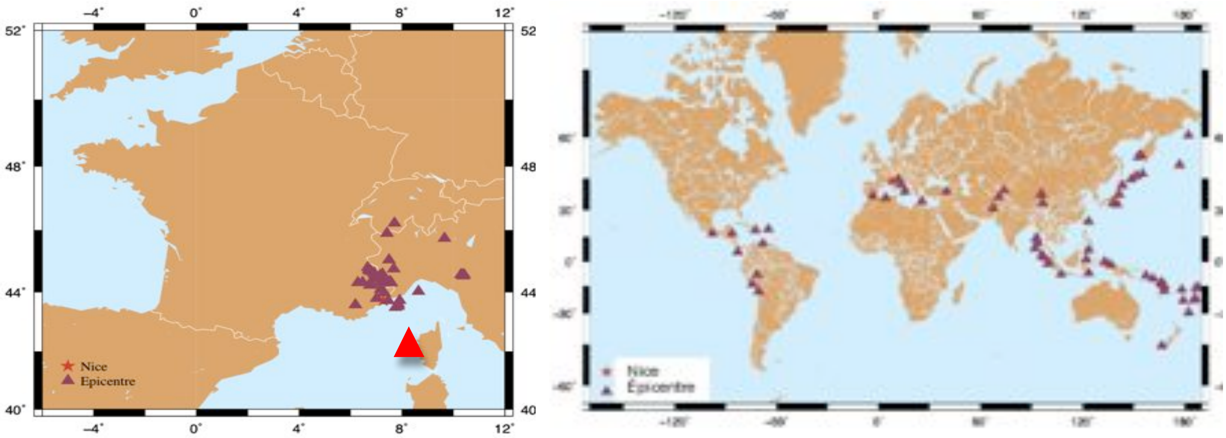

Figure 3. Location of the events used in this study, the red triangle represents the earthquake that produced the strongest shake in Nice during the experiment.

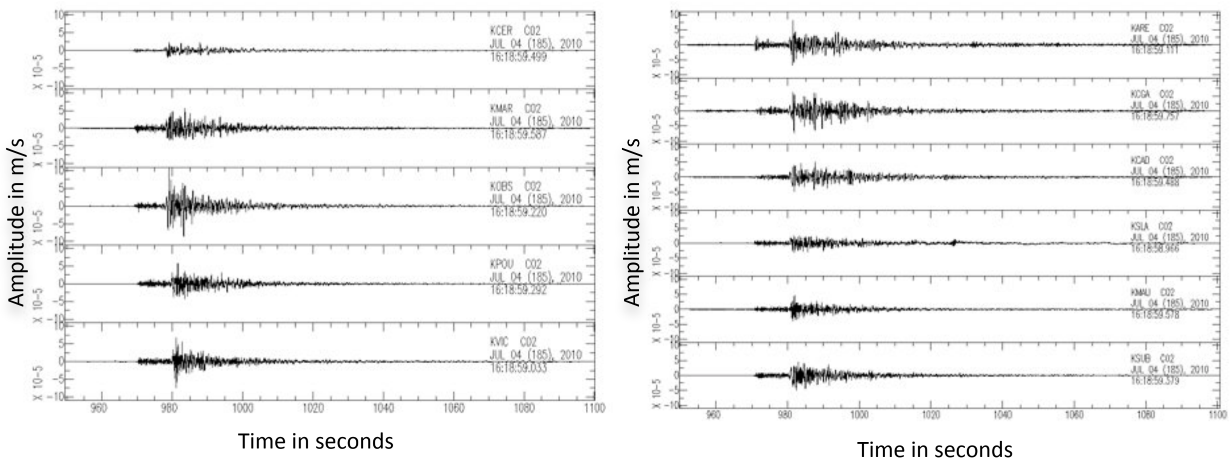

Figure 4. Example of local earthquake recordings (EW component). This event (Mw=3,7) occurred in July, 4th 2010 at 76 km away from KCER station.

Three different spectral ratio computations have been processed. To avoid any misinterpretation, all of three methods are only considering the recordings in the frequency band where the signal-to-noise ratio is larger than 3. The Fourier spectra have been obtained by a standard Fast Fourier Transform scheme (FFT). To process the signal, the time series are tapered with a cosine taper with a length of 10% of the considered window. The resulting Fourier spectra have been smoothed using the Konno and Ohmachi (1998) smoothing technique. The FFT has been computed on a time window including the whole seismic signal. This window is larger for the teleseismic event than for the local one. The combined use of the distant and local earthquake recordings allows us to investigate the site response in a broad frequency band.

Borcherdt and Gibbs described the SSR technique for the first time in 1970. It consists of recording earthquakes on various sites suspected of seismic amplification and comparing the gathered data with simultaneous recordings at a reference station placed directly on a flat-outcropped rock. The method consists in computing the spectral ratio site-over-reference (called also Standard Spectral Ratio, SSR). For a given place, these spectral ratios are function of the earthquake source. According to Field and Jacob (1995), reliable results are only obtained considering a mean of several spectral ratios computed from a significant number of well-distributed earthquakes over a large magnitude and distance range. When this condition is full-filled, the mean spectral ratio can be considered as an estimated transfer function of the investigated site. The main difficulty of the method lies in the choice of the reference station. The critical assumption made is that the surface rock-site record used as a reference is equivalent to the input motion at the base of the soil layers. However, surface rock-site can have a site response of its own, which could lead to an underestimation of the seismic hazard when these sites are used as reference sites (Steidl et al., 1996). In order to select the more appropriate reference station we compute the mean spectral ratio (MSR) and the H-over-V spectral ratio (HVEQ) at pre-selected stations, which are the ones located on rocky outcrops (KACA, KCER, KOBS, KMAR KPOU and KVIC).

Fig 5. gives an example of processing at station KCGA. The reference station used here is KPOU. The individual ratios are shown in the top panels, the mean and the standard deviation are presented in the lower part of the figure. Individual site-to-reference ratios are computed only at frequencies where the signal-to-noise ratio is larger than 3 and the mean curve (the SSR) is evaluated when at least two individual curves exists. Thus with the local events, the SSR is obtained, at this station, only for frequencies larger than 0.7 Hz. On the contrary, the SSR derived from the teleseismic events is only valid below 1.3 Hz. The combined use of local and distant events allows us to determine here the SSR from 0.3 Hz to 10 Hz. Above 10 Hz, the data are to noisy to be used. Between 0.7 Hz and 1.3 Hz the two types of recordings are very consistent. The main amplification is detected around 2Hz. At this frequency the ground motion at station KCGA is on average 6 times larger than at KPOU. The variability of the ratio is there rather important: the maximum ratio is larger than 10 and the lower is close to 1.

An interesting alternative to the SSR computation consists in considering the mean spectrum computed from all recordings instead of one single recording as the denominator of the spectral division. This is particularly useful when the reference station is unknown and allows investigating which station deviates the most from the mean. The MSR technique has been particularly applied to the data of the stations installed on rock sites. It has been derived from the method developed by Wilson and Pavlis (2000) and used recently by Mauffroy et al. (2011).

Following Langston (1979), the H-over-V spectral ratio method was applied to the recordings. In this method the mean FFT of the two horizontal components is divided by the vertical spectrum. Like the SSR, it provides us with an estimate of the transfer function of the site when considering a significant amount of data but it presents the advantage not to have to take into account any reference station. Nevertheless, the amplitude of the ratio can differ from the SSR or MSR ones.

In order to illustrate the method, we show in Fig. 6 the results we obtain at KCGA. The same precaution has been taken into account than for the SSR computation, considering only the data in the frequency band where the signal-to-noise is larger than 3. Here again, we take the advantage of the combined processing of distant and local event to compute the HVEQ on the largest frequency band possible. The result we obtain is very close to the SSR shown in Fig. 5 in terms of frequency and level of amplification. The mean ratio maximum is observed at almost 2Hz with a level of 7.5.

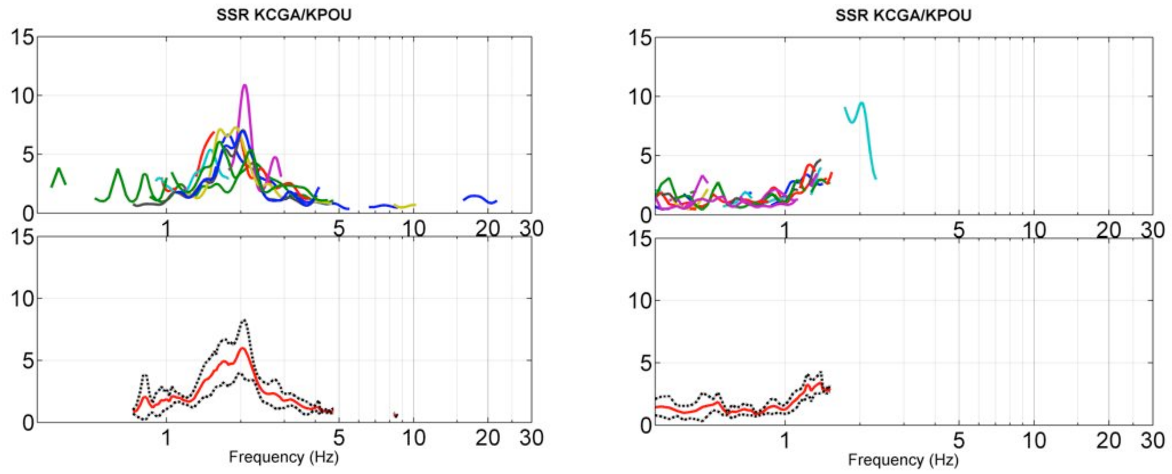

Figure 5. Example of computation at station KCGA: standard spectral ratio (SSR) on local events (left) and teleseismic events. The considered reference station is KPOU. The upper graphs present the results of the computation for all the recordings available at the station. The associated mean (in red) and standard deviation (dotted black) can be seen in the lower graphs.

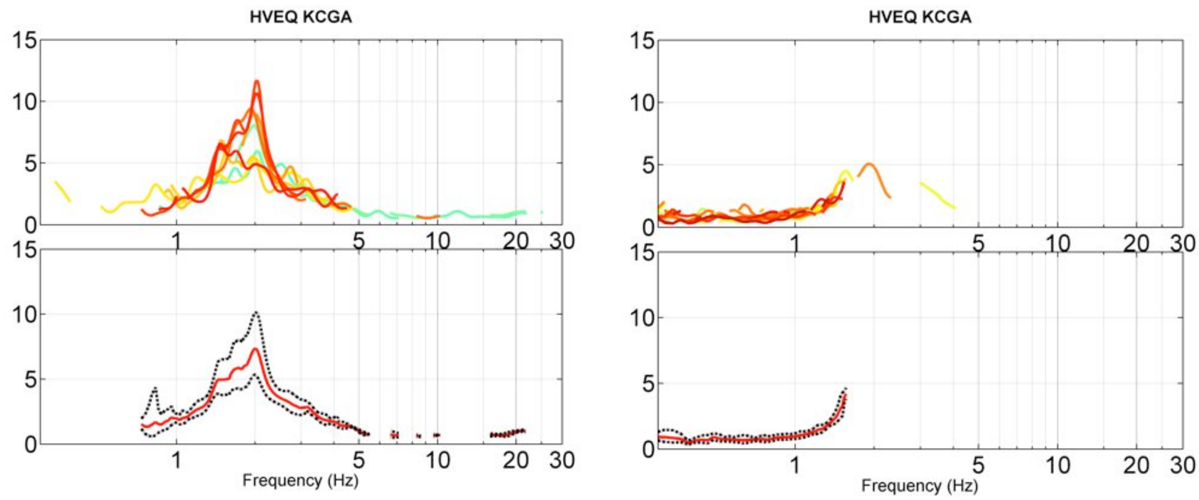

Figure 6. Example of computation at station KCGA: HVEQ spectral ratio on local events (left) and teleseismic events. The upper graphs present the results of the computation for all the recordings available at the station. The associated mean (in red) and standard deviation (dotted black) can be seen in the lower graphs.

3. RESULTS

The mean H-over-V spectral ratios (HVEQ) for the rock sites are shown in Fig. 7. The curves derived from the teleseismic events are plotted together with the ones deduced from the local earthquake data. The mean ratios are figured in red and blue lines for the teleseismic and the local events respectively. The black lines represent one standard deviation over or below the mean. As expected for rock sites, no significant peak is emerging at the six stations. Nevertheless, the ratios present some fluctuations. For frequencies smaller than 1 Hz, KOBS and KACA present similarly high HVEQ ratio but around 3 Hz KOBS exhibits a second peak that is not found on KACA mean ratio. KCER and KPOU show the flattest curve, their mean ratios are very close to 1 for the whole frequency band investigated.

The MSR are very similar using either the local events or the teleseismic ones (Fig. 8). The MSR processing confirms the HVEQ results: all the stations may be considered as references stations. But, looking in details, one can observe that in some frequency bands the data collected at KPOU and KCER show, on average, less amplitude that the other stations. Indeed, between 1.3 Hz and 15 Hz for KCER and between 0.4 Hz and 1.3 Hz for KPOU, the MSR is smaller than 1. For KCER the minimum is reached at 4.10 Hz. At this frequency the MSR is equal to 0.49. At KPOU, the minimum, equal to 0.47, is pointed out at 0.5 Hz. Using these stations as references in the SSR processing may thus slightly overestimate the probed site response in these frequency bands. On the contrary, KOBS is the station where the seismic motion seems to be the most amplified compared to the others. Below 2.3 Hz the MSR at this station is very similar to the one obtained at KACA but a peak can be pointed out around 3 Hz on KPOU MSR that is not seen on KACA mean ratio. At this frequency, the motion at KOBS is on average twice as important as the mean of the motion recorded at the other stations. Both stations are distant from only few meters and the main difference between them is the building in which they are installed. Thus, the peak observed at 3 Hz on KOBS MSR could be linked to the response of the astronomical observatory dome.

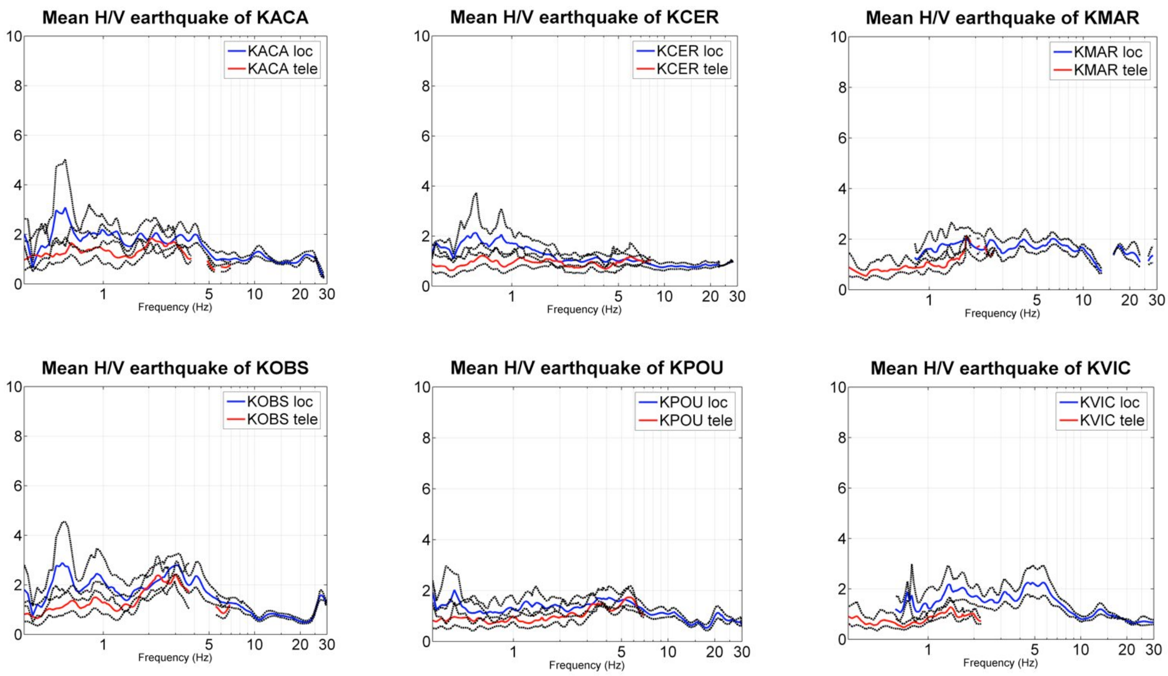

Figure 7. HVEQ computed at the rock sites. The curve in red has been derived from the teleseismic events, the blue one from the local events. The black curves correspond to one standard deviation above or below the mean. KACA, KCER, KMAR and KOBS are located on Mesozoic rocks whereas KPOU and KVIC lay on Pliocene conglomerates.

For the stations in the Var valley, we used finally KPOU as a reference station for the SSR calculation as it combines the advantages of the shortest distance to the Var array and a good rocky response. Furthermore, it lays on the same conglomerates that could be found as the bedrock of the Var alluvium. Fig. 9 gives the SSR for the 6 stations that recorded the seismic ground motion in the Var basin. As expected, the SSR deduced from the teleseismic events allows the computation of the SSR at low frequency whereas the local events help us to define the SSR at higher frequency. For some stations, we do not have any results at high frequencies because of the noise level they are exposed, as they are located in a very busy city area. At KGCA, for instance, the recorded noise over 5 Hz is too much prominent and the SSR could not be computed above this frequency.
From Fig. 9, we notice that the SSR computed with the teleseismic data and the one deduced from the local events are very consistent for the 6 stations. The mean SSR obtained for KMAU is smaller than 2 between 0.3 Hz and 30 Hz. At this station the seismic motion is close to the one recorded at KPOU. The mean ratio at KSUB presents a first peak close to 0.9 Hz reaching almost a factor of 3 and a second amplification at higher frequency, above 2.5 Hz. KSLA presents a peak over a factor of 2 around 2.4 Hz and the SSR at KARE station seems to depict an amplification at about 1 Hz. KCAD and KCGA can somehow be compared: both stations seem to exhibit an amplification of the seismic motion between 1Hz and 4 Hz. At KCGA however the peak is better pronounced. At this station, the SSR maximum reaches a value of 6 at 2.0 Hz.

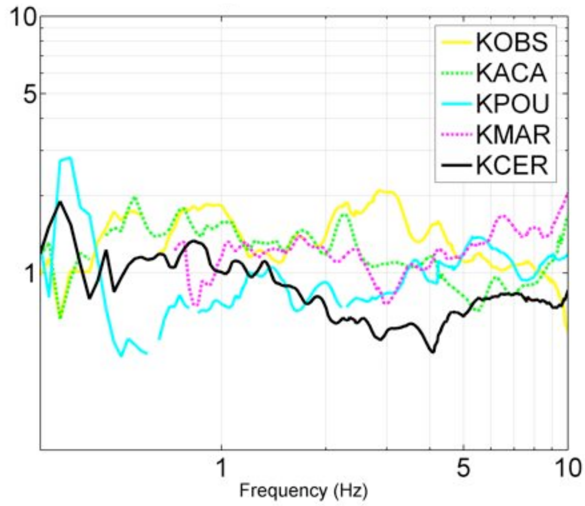

Figure 8. MSSR computed at KACA, KCER, KMAR, KOBS and KPOU.

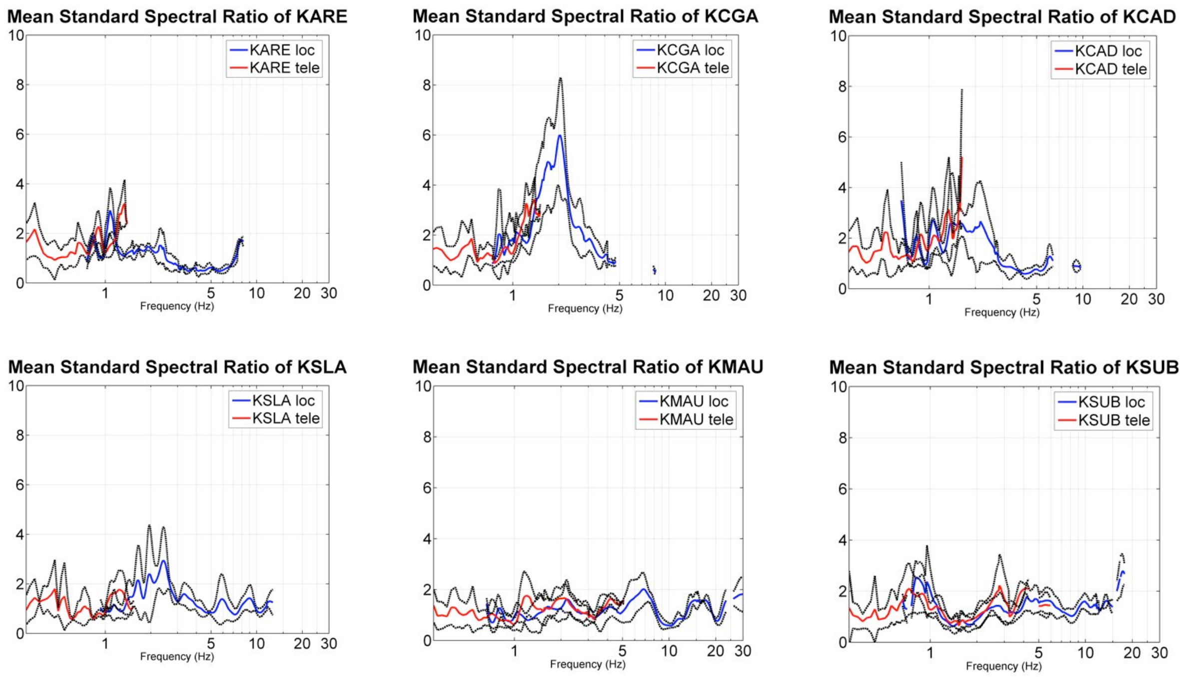

Figure 9. SSR computed at the Var valley sites. The curve in red has been derived from the teleseismic events, the blue one from the local events. The black curves correspond to one standard deviation above or below the mean.

4. DISCUSSION

The data analysis we conducted in this study gives some interesting results. They prove that even if the investigated rock sites can be in a certain extend considered as reference stations, no one shows a perfect flat response over the whole considered frequency band. The absolute reference station does thus not exist as it was already pointed out by several studies in the past (e.g. Chavez-Garcia et al., 1996; Steidl et al., 1996; Tucker et al., 1984). Thereby, we have to be careful using them in the SSR processing and we should stay aware that they could lead to overestimation or underestimation of the site amplification. This can explain also why the level of amplification deduced from SSR and HVEQ computations are often different even if the frequencies the most amplified by the site are well recovered by both techniques.

The computation of the mean spectral ratio introduced by Wilson and Pavlis (2000), is a good tool for

over passing the reference site selection dilemma. The reference is no longer a specific site, but the whole available stations. This statistical technique has been successfully used in topographic site effect studies (e.g. Mauffroy et al., 2011) and is very suitable for the study of the rock sites in Nice.
We found some small amplification at KOBS station that could be related to the building response in which the station is installed. It proves that a reference station should be preferentially put in the free field. KCER seems on the contrary to be subject to deamplification. The observed attenuation of the seismic motion could be due to the localization of the station. Indeed, some previous studies show that the foot of the hill is affected by this kind of deamplification (e.g. Bouchon, 1973). Nevertheless, the RAP permanent station situated at the top of the same hill (NBOR) seems to be also affected by such attenuation when comparing its strong motion recordings with traditional GMPE (Drouet, 2006). This attenuation could thus be linked to the geological structure under the whole Boron hill.
The quaternary deposits in the Var valley are mainly made of pebble, gravel and coarse sand with some lenses of fine sand and clay (Bertrand et al., 2007). The variability of the site response in this basin seems to be very high as it appears on the results obtained at the station of the temporary array set up in the valley. KMAU, laying on an ancient alluvial terrace doesn't show any strong amplification when compared to KPOU. At this station the velocity contrast between the quaternary deposits and the Pliocene bedrock may be not strong enough to produce any resonance, or the quaternary deposit may be very thin. The soil column under this station may also be characterized by a progressive S-wave propagation velocity gradient from the surface to the bedrock. The only station presenting a strong ground motion amplification is KCGA located very close to the basin edge. At this station a clear resonance peak is detected around 2.0 Hz, which is in good agreement with the ambient vibration study conducted previously in the area (Bertrand et al., 2007) and may depict a bedrock depth of about 40 meters. At KCAD, located next to KCGA, the amplification is broadened and at KSLA the main peak is found at slightly higher frequency. At this latter station thus, the bedrock could be located at shallower depth than under KCGA. The Var valley is thus certainly affected by 2D site effect (Semblat et al., 2000) that should be more precisely investigated.

5. CONCLUSION

The city of Nice is prone to strong local site effects. Both topographical and geological features lead in amplification or attenuation of the seismic ground motion at specific frequencies. Several data processing have been conducted in order to recover the seismic site response. We compute classical HVEQ and SSR but we also applied a more statistical approach computing the MSR at the stations set up on a rocky site. This MSR computation is a nice tool to study the specific response of several rock sites. As pointed out by Maufroy et al. (2011), it appears to be a powerful means to study topographical site effect since it does not need any reference station. In this case indeed, the recordings of a given site are compared to the mean of all of the other sites. Our results show a particularly important ground motion de-amplification at a station located at the foot of Mont Boron, a hill that shapes the eastern relief of the city. At this station, the seismic motion around 4.10 Hz is in average half as important as it is at the other rocky sites. Such attenuation has also been observed at the top of the mountain. It may be thus linked to the geological structure of the whole hill. Using the recordings at this station in the SSR computation may thereby lead in overestimating the local site effects.
In the western part of the city, the temporary array helps us to depict the variability of the site responses across the Var valley and gives us more constrain in the local seismic hazard assessment of the area. It appears that the Pliocene conglomerates can be considered as a suitable location for reference station in order to compute the SSR at stations in the Var valley. On the eastern border of the basin, we observe strong amplification reaching a factor of 6 at 2.0 Hz. The sedimentary deposit becoming thicker, this amplification becomes smaller in amplitude and starts at lower frequency towards the center of the valley. Our results are thus in good agreement with the geology of the valley. They should now be compared to the seismic amplification specified in the recent microzoning we produced in the frame of the local seismic prevention plan.

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